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ATMOSPHERIC EFFECTS ON MILLIMETER RADIO WAVES

JANUARY 1980

By
H.K. KOBAYASHI

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US Army Electronics Research and Development Command
ATMOSPHERIC SCIENCES LABORATORY
White Sands Missile Range, NM 88002

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
ASL-TR-0049 ✓

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER
9

4. TITLE (and Subtitle)
6 ATMOSPHERIC EFFECTS ON MILLIMETER RADIO WAVES.

5. TYPE OF REPORT & PERIOD COVERED
R&D Technical Report.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
10 H. K./Kobayashi

8. CONTRACT OR GRANT NUMBER(s)
12 55

9. PERFORMING ORGANIZATION NAME AND ADDRESS ✓
Atmospheric Sciences Laboratory
White Sands Missile Range, NM 88002

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
16
DA Task No. 1L162111AH71

11. CONTROLLING OFFICE NAME AND ADDRESS
US Army Electronics Research and Development Command
Adelphi, MD 20783

12. REPORT DATE
11 Jan[redacted]980

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
14 ERADCOM/ASL-TR-Ø049

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Atmospheric effects	Attenuation by rain
Millimeter waves	Backscatter by rain
Rain	Raindrop-size distribution
Hydrometeors	Turbulence at millimeter wavelengths

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a short survey intended to present the atmosphere's effect on millimeter waves. The emphasis is on rain and raindrop-size distributions. This emphasis is appropriate because rain (the most common nongaseous constituent of the lower atmosphere) also has the greatest effect on millimeter waves, and raindrop-size distribution is needed to compute the theoretical and measured extinction of radio waves.

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20. ABSTRACT (cont)

The pressing need to acquire short-time data on raindrop-size distribution, particularly in the smallest size classes, is emphasized. Likewise, the acquisition of data on atmospheric fluctuations will determine how well millimeter-wave propagation through turbulence will be understood.

PREFACE

The author gratefully acknowledges the aid of Drs. Donald E. Snider and Douglas R. Brown of the US Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico, and the staff of the Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia, in the preparation of this survey.

CONTENTS

INTRODUCTION

Electromagnetic waves traveling through the atmosphere are absorbed, scattered, and refracted by gases, hydrometeors, and particulate matter.[1]

The gases that affect millimeter waves are mainly oxygen and water vapor that have pronounced resonant absorption lines at 22, 60, 118, and 183 GHz.[2] Nonresonant absorption also occurs within the transparent "windows" centered at 35, 94, 140, and 220 GHz, but to a much lesser degree; hence, most research reported to date is at or near these windows.

Hydrometeors are terms for the liquid and solid forms of precipitated atmospheric water vapor. Liquid water is known to scatter electromagnetic waves more strongly than ice because of its larger dielectric constant. In addition, it will attenuate waves strongly because of its higher dielectric loss and thermal dissipation.[3] Consequently, there is general agreement in the literature from theory and observation that rain, the most frequently encountered hydrometeor of the lower atmosphere, is of paramount importance in millimeter wave propagation.[4,5] Therefore, this report will focus initially on absorption and scattering by rain, and a brief account of fog and clouds will follow. The literature on melting hydrosols and their effect on millimeter waves is virtually nonexistent, although nascent laboratory work has begun.[6]

Particulate matter (smoke, dust, etc.) has a small dielectric constant compared to water and is not considered as important as the hydrometeors.[1] Moreover, it has been poorly studied at millimeter

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[1]F. B. Dyer and N. C. Currie, 1978, "Environmental Effects on Millimeter Radar Performance," EPP Symposium, Neubiberg bei München, Germany

[2]J. M. Waters, 1976, "Absorption and Emission by Atmospheric Gases," Methods of Experimental Physics, 12(B):142

[3]K. L. S. Gunn and T. W. R. East, 1954, "The Microwave Properties of Precipitation Particles," Quart J Roy Meteorol Soc, 80:522

[4]K. Fischer, 1978, "Atmospheric Influences on the Millimeter and Submillimeter Wave Propagation," EPP Symposium, Neubiberg bei München, Germany

[5]J. H. Rainwater, 1977, "Weather Affects MM Wave Missile Guidance Systems," Microwaves, September, p. 62

[6]D. L. Bryant and L. J. Auchterlonie, 1979, "Measurement of the Extinction Cross-sections of Dry and Wet Ice Spheres at 35 GHz," Electronics Letters, 15:52

wavelengths,[5,7] and adequate discussion at this time is difficult.

Turbulence and its effect on refracting millimeter waves have been studied very little, but are potentially important atmospheric features. These aspects will be discussed at the close of this survey.

RAIN

Beginning at the turn of the century with Gustav Mie, the theoretical effect of particles on electromagnetic waves has been studied continually, notably in cases where particles are assumed spherical, or nearly so, and their diameters are considered small compared to the wavelength of the incident radiation. This report will show that difficulties in understanding this effect are not in the theoretical computations, which are becoming more tractable yearly with rapid advances in computer technology, but in the paucity and unreliability of meteorological data regarding the spatial and temporal distribution of raindrop-size classes.

Collectively, scattering (S) and absorption (A) by a single particle are termed extinction (E) or alternatively, attenuation. Then by the usual radar definition of target cross section (σ), we get $\sigma_E = \sigma_A + \sigma_S$. This nomenclature and the usage of Q for corresponding normalized cross sections, where $Q = \sigma \div \pi D^2/4$ (D = drop diameter), have been fairly consistent as papers written in 1954,[3] 1966,[8] and 1977[7] will attest. Mie calculations of σ involve the index of refraction for water (m), which is complex at millimeter wavelengths, difficult to assess experimentally, and very temperature dependent. Mitchell has tabulated values for m from wavelengths λ = 1 to 100 mm for 0, 10, 18, and 20°C.[8] Some idea of how the cross sections vary with D and λ can be obtained from figures 1 and 2. The values for m are at 18°C. Note how the total attenuation σ_t increases as the millimeter frequency increases, and how small raindrops, typically less than 1 mm diameter, become important in backscatter σ_{BS} as frequency increases. Theoretical calculations sum up the effect of every particle in a volume, and therefore depend on reliable field data of drop-size distribution.

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[5]J. H. Rainwater, 1977, "Weather Affects MM Wave Missile Guidance Systems," Microwaves, September, p. 62

[7]W. L. Gamble and T. D. Hodgens, 1977, "Propagation of Millimeter and Submillimeter Waves," US Army MIRADCOM Technical Report TE-77-14, AD B023622

[3]K. L. S. Gunn and T. W. R. East, 1954, "The Microwave Properties of Precipitation Particles," Quart J Roy Meteorol Soc, 80:522

[8]R. L. Mitchell, 1966, "Radar Meteorology at Millimeter Wavelengths," Aerospace Corporation, Report TR-669(6230-46)-9, AD 488085

Direct Measurement of Raindrop Sizes

There are apparently four general techniques for obtaining drop-size classes at one site:

1. Physical capture of drops by an absorbing agent with a known surface area[9,10,11,12]

2. Photographing drops within a known volume[10,12,13,14]

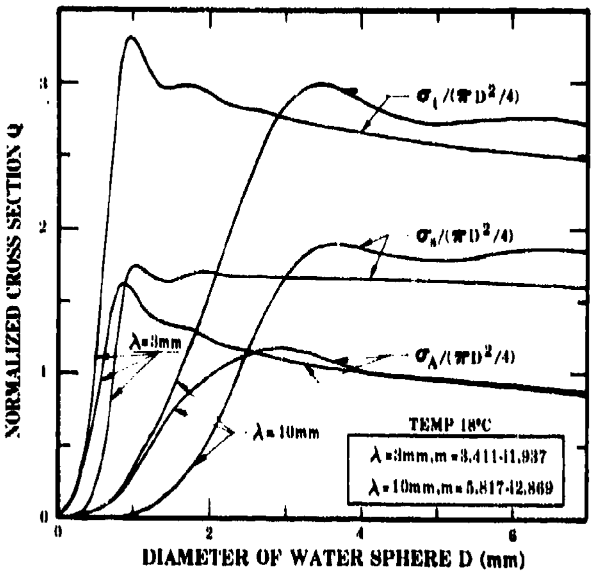

Figure 1. Absorption, scattering, and total attenuation cross sections of water spheres (ref 8).

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[9]L. J. Anderson, J. P. Day, C. H. Freres, and A. P. D. Stokes, 1947, "Attenuation of 1.25-Centimeter Radiation Through Rain," Proc IRE, 35:354

[10]J. Joss and A. Waldvogel, 1969, "Raindrop Size Distribution and Sampling Size Errors," J Atmos Sci, 26:566

[11]J. O. Laws and D. A. Parsons, 1943, "The Relation of Raindrop Size to Intensity," Trans Am Geophys Union, 24:452

[12]S. Ugai, K. Kato, M. Nishijima, T. Kan, and K. Tazaki, 1977, "Fine Structure of Rainfall," Ann des Télécom, 32:422

[13]M. A. Jones, 1959, "The Shape of Raindrops," J Meteorol, 16:504

[14]R. Cataneo and G. E. Stout, 1968, "Raindrop-Size Distributions in Humid Continental Climates, and Associated Rainfall Rate-Radar Reflectivity Relationships," J Appl Meteorol, 7:901

3. Electromechanically by translating drop momenta to electric analogs[15,16]

4. Electrostatically by measuring inherent or induced charges of raindrops[17,18,19,20]

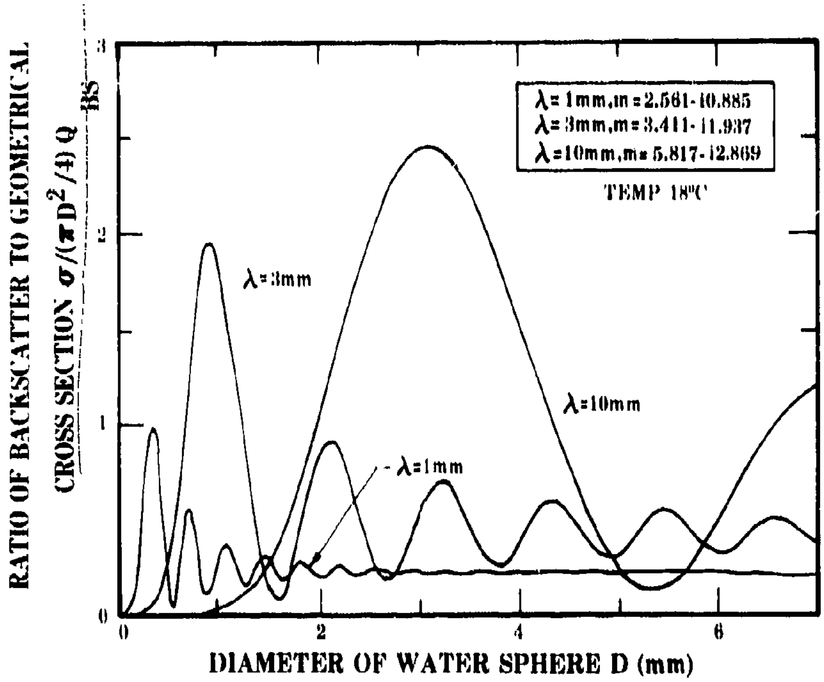

Figure 2. Backscatter cross section of water spheres (ref 8).

[15] A. Waldvogel, 1974, "The N_0 Jump of Raindrop Spectra," J Atmos Sci, 31:1067

[16] L. J. Bruer and R. K. Kreuels, 1977, "Rainfall Drop Spectra Intensities and Fine Structures on Different Time Bases," Ann des Télécom, 32:430

[17] S. G. Bradley and C. D. Stow, 1974, "The Measurement of Charge and Size of Raindrops: Part I. The Disdrometer," J Appl Meteorol, 13:114

[18] U. H. W. Lammers, 1969, "Electrostatic Analysis of Raindrop Distributions," J Appl Meteorol, 8:330

[19] M. M. Kharadly, J. D. McNicol, and J. B. Peters, 1978, "Measurement of Attenuation Due To Rain at 74 GHz," EPP Symposium, Neubiberg bei München, Germany

[20] W. P. Winn, 1969, "A Device for Measuring the Radii of Raindrops," J Appl Meteorol, 8:335

From the beginning, many investigators encountered problems. Drop sizes could vary unpredictably during a single shower[9] as well as from storm to storm.[21] Figure 3 taken from Lammers[18] is typical of results obtained by meteorologists during intervals of a few minutes. Direct criticisms include the generally poor statistical handling of field data[22,23] and the sampling size being an order of magnitude too small for valid estimations.[10]

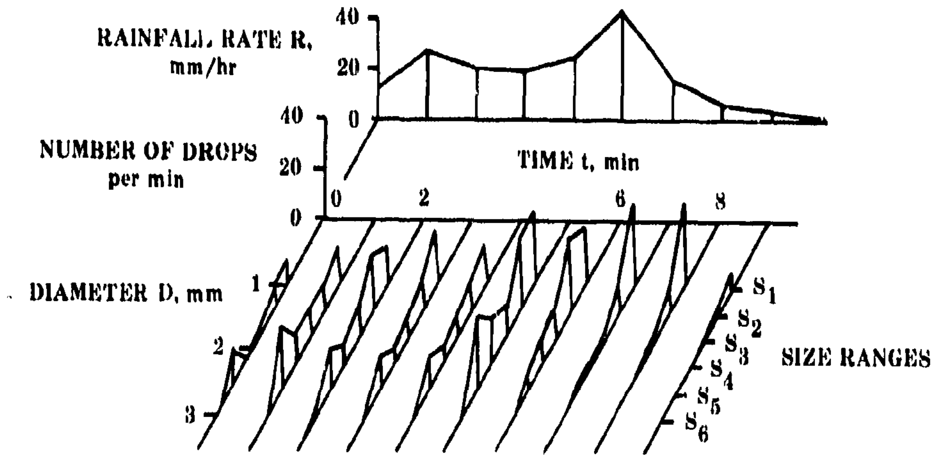

Figure 3. Drop sizes measured during a heavy shower (ref 18).

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[9]L. J. Anderson, J. P. Day, C. H. Freres, and A. P. D. Stokes, 1947, "Attenuation of 1.25-Centimeter Radiation Through Rain," Proc IRE, 35:354

[21]Miyuki Fujiwara, 1965, "Raindrop-size Distribution from Individual Storms," J Atmos Sci, 22:585

[18]U. H. W. Lammers, 1969, "Electrostatic Analysis of Raindrop Distributions," J Appl Meteorol, 8:330

[22]P. L. Smith and C. P. Laco, 1978, "Techniques for Fitting Size Distribution Functions to Observed Particle Size Data," Am Meteorol Soc, 18th Conference on Radar Meteorology, 28-31 March 1978, Atlanta, GA

[23]C. P. Laco, 1978, "A Technique for Fitting Exponential Functions to Precipitation Particle Size Data," Institute of Atmospheric Sciences, Report 78-3, S. Dakota School of Mines and Technology, Rapid City, SD 57701

[10]J. Joss and A. Waldvogel, 1969, "Raindrop Size Distribution and Sampling Size Errors," J Atmos Sci, 26:566

One criticism worth discussing separately is the scarcity of data on raindrops smaller than 0.5 mm. It will be recalled from the previous page that the smaller drops contribute more to attenuation and backscatter at the shorter millimeter wavelengths. Uagi et al[12] showed that many drops exist in the 0.05 and 0.5 mm range which they claim had not been previously measured. Their claim is not entirely valid since the widely used Joss and Waldvogel disdrometer employing the third technique listed above has a lower limit of 0.3 mm.

The drop-size distributions of Laws and Parsons[11] and Marshall and Palmer[24] of the 1940's are still the most widely quoted today. Marshall and Palmer found that their data and those of Laws and Parsons empirically fitted the curve

$$N_D = N_o e^{-\Lambda D} . \tag{1}$$

where D = diameter mm, $N_o = 0.08\ cm^{-4}$, $\Lambda = 4.1\ R^{-0.21}\ cm^{-1}$, and R = rainfall rate mm/hr.

Figure 4 taken from Marshall and Palmer's paper superimposes equation (1) and the data from both papers for three rainfall rates. Note that the Marshall-Palmer relation has more drops in the small sizes than the Laws-Parson data. Examples of Ugai et al in figure 5 have even greater numbers of drops in the small range.

The Joss and Waldvogel drop-size distribution based on equation (1) is the third most quoted distribution. The usefulness of this distribution lies in the introduction of another dimension by changing N_o and Λ and characterizing a rain event as a drizzle, widespread, or thunderstorm.[15] Widespread rainfall has the "average" condition $N_o = 0.07$ and $\Lambda = 4.1\ R^{-0.21}$, and a comparison with equation (1) shows that it is very similar to the Marshall-Palmer relation.

To find the drop-size frequency distribution in a volume (which is needed to find the attenuation usually expressed in decibels per kilometer), the surface drop distribution and the fall velocity of drop-size classes must be known. For the latter, the careful work of Gunn and Kinzer on the

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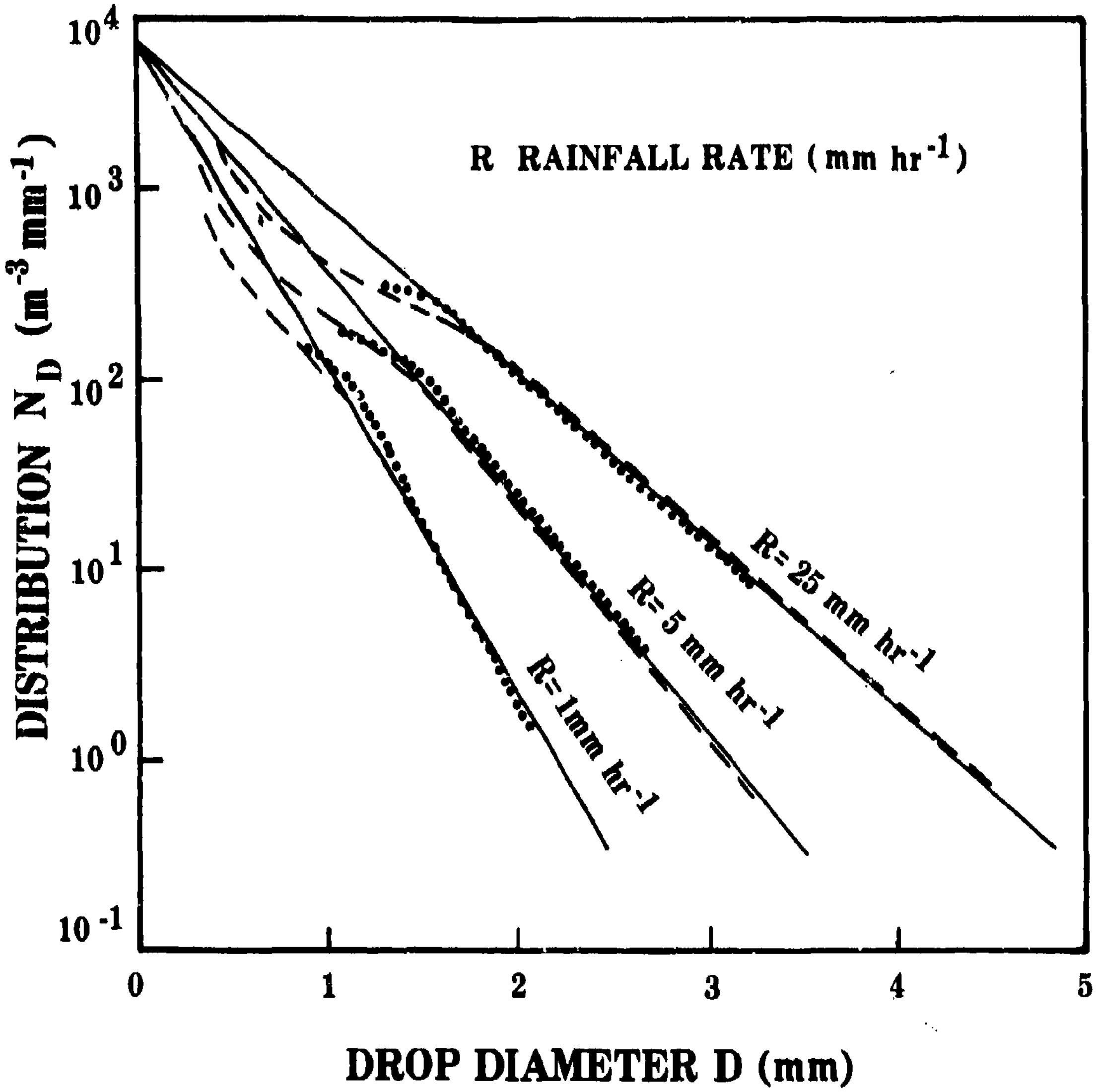
[12]S. Ugai, K. Kato, M. Nishijima, T. Kan, and K. Tazaki, 1977, "Fine Structure of Rainfall," Ann des Télécom, 32:422

[11]J. O. Laws and D. A. Parsons, 1943, "The Relation of Raindrop-size to Intensity," Trans Am Geophys Union, 24:452

[24]J. S. Marshall and W. McK. Palmer, 1948, "The Distribution of Raindrops with Size," J Meteorol, 5:165

[15]A. Waldvogel, 1974, "The N_o Jump of Raindrop Spectra," J Atmos Sci, 31:1067



Solid line-equation 1 (ref 24)
Dashed line-Laws-Parsons (ref 11)
Dotted-Marshall-Palmer (ref 24)

Figure 4. Distribution of raindrops solid line-equation 1 (ref 24).

terminal velocity of water droplets[25] has been almost universally accepted for the past 30 years. Some attempts have been made to refine their values;[26,27] however, recent work on photographing falling raindrops is still in fair agreement with the original work.[12]

Keizer et al[28] reviewed the calculations required to find the distribution in a volume from original or theoretical measurements. An example of this type of computation is figure 5 featuring data ranging into sizes smaller than 0.5 mm which are rarely available. It is apparent that for any given drop size, the number of drops increases uniformly with increasing rainfall intensity. This result is very different from any previous investigations and needs verification.

Attenuation by Rain, the aR^b Relation

In their review paper of 1954, Gunn and East credit J. W. Ryde as the one who first realized the importance of rain attenuation and backscatter at radar frequencies.[3] Ryde's paper of 1946 offered the

[25]R. Gunn and G. D. Kinzer, 1949, "The Terminal Velocity of Fall for Water Droplets in Stagnant Air," J Meteorol, 6:243

[26]A. N. Dingle and Y. Lee, 1972, "Terminal Fallspeeds of Raindrops," J Appl Meteorol, 11:877

[27]E. X. Berry and M. R. Pranger, 1974, "Equations for Calculating the Terminal Velocities of Water Drops," J Appl Meteorol, 13:108

[12]S. Ugai, K. Kato, M. Nishijima, T. Kan, and K. Tazaki, 1977, "Fine Structure of Rainfall," Ann des Télécom, 32:422

[28]W. P. M. N. Keizer, J. Snieder, and C. D. de Haan, 1978, "Rain Attenuation Measurements at 94 GHz: Comparison of Theory and Experiment," EPP Symposium, Neubiberg bei München, Germany

[3]K. L. S. Gunn and T. W. R. East, 1954, "The Microwave Properties of Precipitation Particles," Quart J Roy Meteorol Soc, 80:522

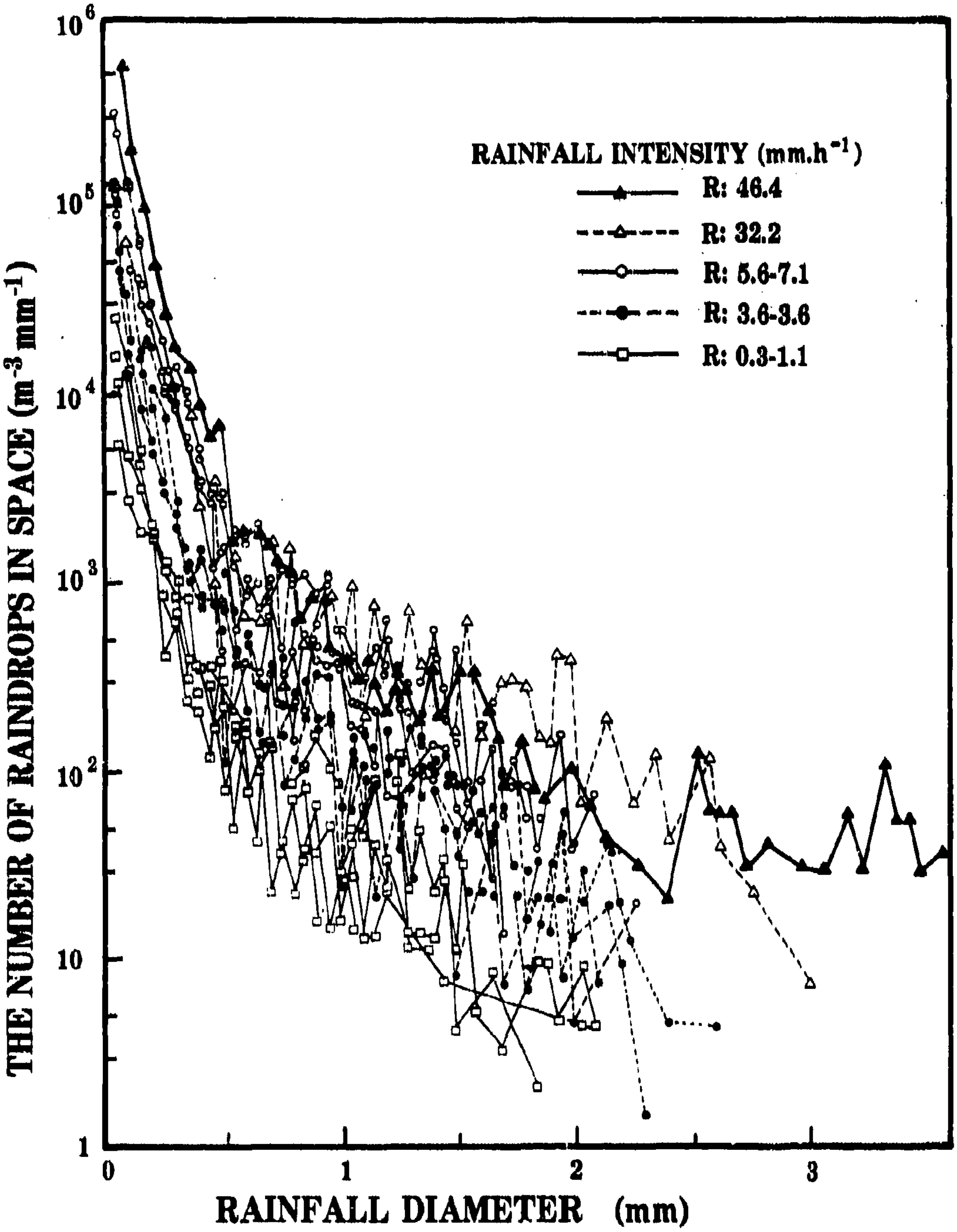


Figure 5. Some examples of density of the distribution in space by calculation using the falling velocity of Gunn and Kinzer (ref 12).

following linear expression (in his notation) for the average attenuation along a path in decibels per kilometer:[29]

$$dB/km = kp \tag{2}$$

where k depends on wavelength and temperature, and p "varies widely" with rainfall intensity and geographical area.

Ryde fully realized the importance of path length, drop-size distribution and wavelength, although his expressions did not include these variables. Early investigators soon realized that attenuation could be better represented in the form:

$$A = aR^b , \tag{3}$$

where

A = attenuation in decibels per kilometer,

R = rainfall rate in millimeters per hour, and

a and b are frequency and temperature dependent.

In practice, simultaneous values of A and R are plotted and a curve of the form of equation (3) fitted to the points. The rainfall rate R is found from the drop-size distribution if a disdrometer or an equivalent instrument is available, or by means of the more standard tipping bucket rain gauge. The widely scattered points corresponding to pairs of A-R values in figures 6 and 7 reveal the difficulty in computing a least-square, or any other kind of fit, to the data. Highly scattered points also indicate that drop sizes will vary tremendously during the course of a single rain event. This was seen as early as 1954 when Gunn and East listed ten values for the "constants" a and b of equation (3) based on original size data taken in various parts of the world by several workers.[3] Numbers ranged from 127 to 505 for a and from 1.041 to 2.29 for b, indicating that attenuation could vary as much as 2 or 3 either way from an average value of aR^b for a given rainfall rate (i.e., a and b given by average values).

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[29]J. W. Ryde, 1946, "The Attenuation of Centimeter Radio Waves and the Echo Intensities Resulting from Atmospheric Phenomena," JIEE, Vol 93, Part IIIA, No. 1, p. 101

[3]K. L. S. Gunn and T. W. R. East, 1954, "The Microwave Properties of Precipitation Particles," Quart J Roy Meteorol Soc, 80:522

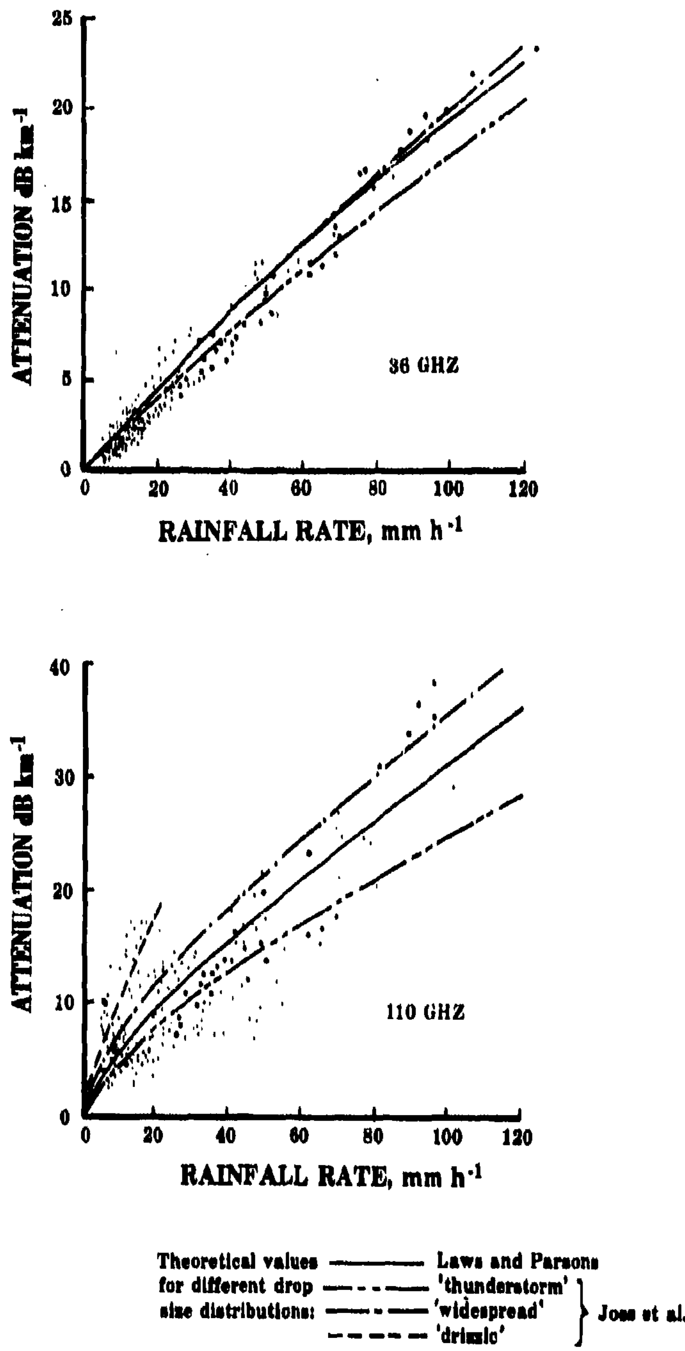

Figure 6. Variation of attenuation with rainfall rate (ref 38).

Conflicting and widely varying results from field measurements in the two decades following World War II prompted Medhurst to write his frequently cited comprehensive survey of 1965.[30] He reviewed, tabulated, and graphed the then extant rainfall attenuation data spanning λ = 4 to 32 mm, and in each experiment employed from 1 to 13 rain gauges. A few even took raindrop-size distribution, which yields rainfall rate when the fall velocity of raindrops is accounted for (see, for example, Anderson et al[9] who used both rain gauges and drop counts). Medhurst found that in practically all 15 cases there was a tendency for measured attenuation to be higher than the maximum theoretically attainable. He concluded that possible errors may be due to:

1. Inadequacy of the theory to account for multiple-scattering along the path, and

2. " . . . The rain structure being more complex than has been assumed."

In fairness to Medhurst because of the criticism from Crane and others (Crane[31] and his later papers, Olsen et al,[32] and Watson[33]), his paper should be judged in the light of information available to him at that time. He explained in detail why Ryde's application of Mie theory seemed inadequate to him and tried to show this graphically with each of the 15 cases he studied. Also, he analyzed and tabulated his remarks on the taking of rainfall rate and thought only the technique of Anderson et al was above criticism. He deemed Mie theory inadequate, not inappropriate, and appeared to give poor meteorological instrumentation and interpretation at least equal fault for inconsistent results.

In 1971 Crane argued that Mie theory was appropriate and that experiments over a short path with closely spaced rain gauges would show that the fault lay with the inadequate meteorological data.[31] From his work with

---

[30]R. G. Medhurst, 1965, "Rainfall Attenuation of Centimeter Waves: Comparison of Theory and Measurement," IEEE Trans Antennas Propagat, AP-13:550

[9]L. J. Anderson, J. P. Day, C. H. Freres, and A. P. D. Stokes, 1947, "Attenuation of 1.25-Centimeter Radiation Through Rain," Proc IRE, 35:354

[31]R. K. Crane, 1971, "Propagation Phenomena Affecting Satellite Communication System Operating in the Centimeter and Millimeter Wavelength Bands," Proc IEEE, 59:173

[32]R. L. Olsen, D. V. Rogers, and D. B. Hodge, 1978, "The aR^b Relation in the Calculation of Rain Attenuation," 1978, IEEE Trans Antennas Propagat, AP-26:318

[33]M. Watson, 1976, "Survey of Measurements of Attenuation by Rain and other Hydrometeors," Proc IEEE, 123:863

L-band radar backscatter from New England showers,[34,35] Crane believed that a large area of light rain contains many small intense showers and better spatial resolution of rainfall rate is needed to predict attenuation. In 1974 Crane reported the results of his well-known experiment using simulated rain of known drop-size distribution.[36] He concluded that the field measurements and the theoretical calculations based on Mie single-scattering theory for water spheres were in agreement at 34 GHz, and the discrepancies noted by Medhurst and a few later workers are due to inadequate meteorological characterization.

In table 1, rain attenuation investigations along a one-way path at about 30 GHz or higher are listed in chronological order. Two-way paths as in radar backscatter will be discussed in the next section. Table 1 and the tables in the summary paper by Watson[33] comprise most of the open literature on the subject. Not listed are several theoretical studies, notably by the Soviets, described by Richard et al[37] who use the distribution of Marshall and Palmer and other Western investigators as well as their own. Table 1 experiments express the aR^b relation with comparative plots of measured and theoretical attenuation versus rainfall rate. The rate in turn is derived from original drop distributions and/or conventional rain gauge data modified in the later experiments for fast sampling, and/or from known distributions such as the Marshall-Palmer. Some who wished to bracket their scattered data points also include Joss's distributions for the extremes of "thunderstorm" and "drizzle."[38] A reading of these references will reveal that there is general agreement between measured and theoretical attenuations, particularly below 50 GHz, and thus Crane's criticism of Medhurst appears justified.

At this time then, simultaneous measurements--one below 50 GHz and one above--through the same rain path are valuable for comparative purposes. Figure 6 from Zavody and Harden[38] contrasts such a pair of frequencies:

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[34]R. K. Crane, 1968, "Simultaneous Radar and Radiometer Measurements of Rain Shower Structure," Lincoln Lab MIT Technical Note 1968-33, AD 678079

[35]R. K. Crane, 1966, "Microwave Scattering Parameters for New England Rain," Lincoln Lab MIT Technical Report 426, AD 647798

[36]R. K. Crane, 1974, "The Rain Range Experiment-Propagation Through A Simulated Rain Environment," IEEE Trans Antennas Propagat, AP-22:321

[33]M. Watson, 1976, "Survey of Measurements of Attenuation by Rain and Other Hydrometeors," Proc IEEE, 123:863

[37]V. W. Richard, J. E. Kammerer, and R. G. Reitz, 1977, "140-GHz Attenuation and Optical Visibility Measurements of Fog, Rain and Snow," Ballistic Research Laboratory, Memo Report ABRL-MR-2800, Aberdeen Proving Ground, MD 21005

[38]A. M. Zavody and B. N. Harden, 1976, "Attenuation/Rain-rate Relationships at 36 and 110 GHz," Electronics Letters, 12:422

TABLE 1. RAIN ATTENUATION EXPERIMENTS - ONE-WAY PATHS AT MILLIMETER WAVELENGTHS*

Reference Number	Year	Author(s)	Frequency (GHz)	Path length (km)	Meteorological Instrumentation
Selected bibliography	1970	Semplak, R. A.	30.9	1.9	Four rain gauges along path
36	1974	Crane, R. K.	33.9	0.305	Drop size camera Simulated rain
Selected bibliography	1975	Harden, B. N., et al	110 110	2.65 0.215	Four "rapid response" rain gauges variously located
38	1976	Zavody, A. M., Harden, B. N.	36, 110	0.22	Four rain gauges along path record at 20-s intervals One "electromechanical" disdrometer
37	1977	Richard, V. W., et al	140	0.725	Three tipping bucket rain gauges along path
Selected bibliography	1977	Valentin, R.	29, 39	2.0	Ten tipping bucket rain gauges along path record at 10-s intervals
28	1978	Keizer, W. P., et al	94	0.935	Three rapid response rain gauges One "electromechanical" disdrometer
41	1978	Ho, K. I., et al	36, 110	4.1	One "electronic" rain gauge records at 20-s intervals

*For experiments below 30 GHz, see Watson's comprehensive survey (ref 33).

36 and 110 GHz. Despite the compressed ordinate scale of the 110-GHz attenuation, the sensitivity to smaller drop sizes is evident in the more divergent theoretical curves and the greater scattering of measured data points. The authors appeared satisfied with the results at 35 GHz. Two plausible explanations were offered for the wide scattering of points at 110 GHz. The first was that drops 0.5 mm or less were not counted due to equipment limitations, and there was no way to check the original against the theoretical drop-size distributions. The second is an error due to the sensitivity of small drops to updrafts and downdrafts. This is a serious problem since the number reaching the disdrometer and the fall velocity would change unpredictably. No longer would the Gunn and Kinzer estimates for the small drops apply because these were done in stagnant air.[25] On anotner point, the authors comment that their calculations show that whether a raindrop is modeled as a sphere or a spheroid is significantly less important to attenuation at 110 GHz than at 36 GHz. They based their calculations on Oguchi[39] who extended Mie theory to aspherical drops and their effect on centimeter and millimeter waves. One explanation of this insensitivity put forth by others is that at higher millimeter wavelengths, small drops contribute more to attenuation and deform very little during their fall through space.[37,40] At lower frequencies, shape is unimportant since small drops contribute little to attenuation.

Another distinct advantage of dual frequency experiments exploited by Zavody and Harden[38] and Ho et al[41] is the elimination of rainfall rate and any attendant measurement errors by plotting attenuation at the two frequencies against each other. Theoretical attenuation curves from original or known drop-size distributions can be superimposed on the plot for comparison. Both papers report good agreement with Laws-Parsons or Joss distributions.

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[25]R. Gunn and G. D. Kinzer, 1949, "The Terminal Velocity of Fall for Water Droplets in Stagnant Air," J Meteorol, 6:243

[39]T. Oguchi, 1973, "Attenuation and Phase Rotation of Radio Waves Due to Rain: Calculations at 19.3 and 34.8 GHz," Radio Sci, 8:31

[37]V. W. Richard, J. E. Kammerer, and R. G. Reitz, 1977, "149-GHz Attenuation and Optical Visibility Measurements of Fog, Rain and Snow," Ballistic Research Laboratory, Memo Report ABRL-MR-2800, Aberdeen Proving Ground, MD 21005

[40]J. Sander, 1975, "Rain Attenuation of Millimeter Waves at $\lambda = 5.77$, 3.3, and 2mm," IEEE Trans Antennas Propagat, AP-23:213

[38]A. M. Zavody and B. N. Harden, 1976, "Attenuation/Rain-rate Relationships at 36 and 110 GHz," Electronics Letters, 12:422

[41]K. I. Ho, N. D. Mavrokoukoulakis, and R. S. Cole, 1978, "Rain-induced Attenuation at 36 GHz and 110 GHz," IEEE Trans Antennas Propagat, AP-26:873

The recent work by Keizer et al in 1978[28] at 94 GHz merits separate discussion for its clarity of presentation and attention to important details. It includes a thorough explanation of how drop-size distribution is obtained by the incorporation of drop-size class data into density and rainfall rate expressions. Sources of error are discussed with care. For instance, the results of a wetting test on the antenna are presented in a table listing wetting condition versus loss in decibels. Fluctuations of 5.8 dB or over for a wet antenna or radome are believed unacceptable for short paths by the authors. The results of their experiment are seen in figures 7 and 8. Satisfactory agreement between measured and calculated attenuations at most rainfall rates is evident. But at low rates, there is a tendency for measured attenuation to be higher. According to the authors, a plausible cause is the inability of the disdrometer to record drops smaller than 0.3 mm diameter. This seems reasonable since the attenuation calculated from their disdrometer data would underestimate attenuation at this high millimeter frequency. It is worth noting that this calculated attenuation (shown as + in figure 7) agrees very well with the theoretical curves, thus bringing up the possibility that the number of small drops is underestimated when data are extrapolated to diameters below 0.3 mm. Extrapolation has been the rule for the Laws-Parsons with diameters less than 0.5 mm, Marshall-Palmer less than 1.0 mm, and Joss et al less than 0.3 mm.[10,11,24] The data of figure 5 of Ugai et al need to be verified because of the importance of small drop sizes at the shorter millimeter wavelength.

A recent important paper on the aR^b relation is that of Olsen, Rogers, and Hodge.[32] In their introduction, the authors state that Medhurst's doubts on theoretical calculations[30] have been repudiated in recent years with improved rain rate sampling techniques and that a more theoretical approach to this empirical relation is due. First, the authors show $A = aR^b$ (equation (3)) to be an approximation to an infinite series

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[28]W. P. M. N. Keizer, J. Snieder, and C. D. de Haan, 1978, "Rain Attenuation Measurements at 94 GHz: Comparison of Theory and Experiment," DPP Symposium, Neubiberg bei München, Germany

[10]J. Joss and A. Waldvogel, 1969, "Raindrop Size Distribution and Sampling Size Errors," J Atmos Sci, 26:566

[11]J. O. Laws and D. A. Parsons, 1943, "The Relation of Raindrop Size to Intensity," Trans Am Geophys Union, 24:452

[24]J. S. Marshall and W. McK. Palmer, 1948, "The Distribution of Raindrops with Size," J Meteorol, 5:165

[32]R. L. Olsen, D. V. Rogers, and D. B. Hodge, 1978, "The aR^b Relation in the Calculation of Rain Attenuation," 1978, IEEE Trans Antennas Propagat, AP-26:318

[30]R. G. Medhurst, 1965, "Rainfall Attenuation of Centimeter Waves: Comparison of Theory and Measurement," IEEE Trans Antennas Propagat, AP-13:550

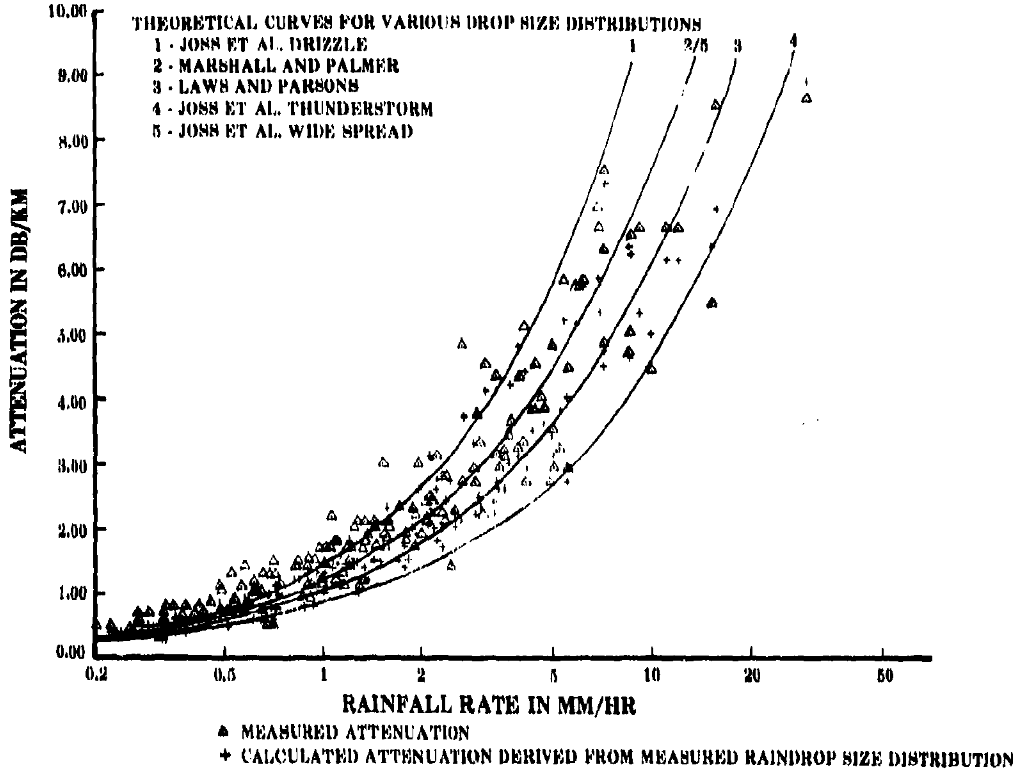

Figure 7. Measured and calculated rainfall attenuation versus rainfall rate at 94 GHz (ref 28).

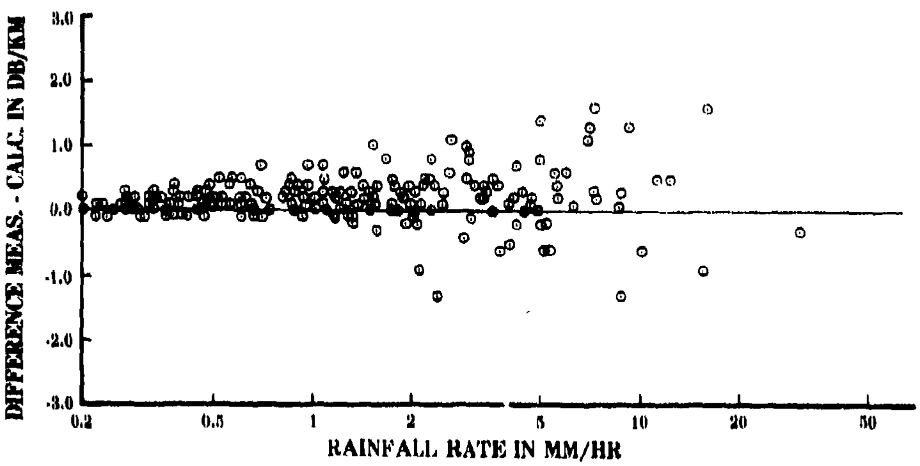

Figure 8. Difference of measured and calculated rainfall attenuation (ref 28).

relation which includes the effect of frequency, rain temperature, and drop-size distribution parameters in the higher order terms. The drop-size distribution, in turn, is shown to be an approximation of a modified gamma function. Next, to facilitate calculations at single frequencies for workers wanting to obtain attenuation directly, three tables corresponding to 20°C, 0°C, and -10°C were generated from Mie computations for spherical drops. Values for a and b for 41 frequencies between 1 and 1000 GHz for five drop-size distributions are listed in each table. The authors' comments on the drop-size distributions and their choice of two distributions to characterize the Laws-Parsons values are worth reading carefully. Finally, Olsen et al derive analytic expressions for a and b from rigorous Mie calculations which are more amenable to computer generation of multiple-frequency curves. The frequency band of 1 to 1000 GHz is divided into four segments, each with four power law relationships of the form $A = aR^b$. Two conclusions by the authors are considered here:

1. " . . . The results show the parameters a and b to be least sensitive to drop-size distribution in the frequency range 10 - 30 GHz. This is also the range where the relation $A = aR^b$ is most accurate."

2. Above 10 GHz, the tabulated values of the Laws-Parsons distribution at 0°C is recommended. A "high" rain rate or a "low" rain rate value may be chosen for a frequency.

A summary of what has been presented so far in this section shows that agreement between measured and theoretical attenuation has been better since Medhurst's time. This better agreement is due, at least partly, to improved rain sampling by increased usage of fast-response disdrometers and rain gauges. There is an awareness of the importance of sampling periodically at faster rates rather than relying on cumulative data. Watson[33] reports that a rain gauge with a response slower than 15 s will underestimate rainfall intensity at a site and will result in a prediction of low attenuation as reported by Medhurst and other workers 10 years ago.

In future research, the parameters of existing drop-size distributions need to be reexamined. Although the Laws-Parsons distribution of 1943 in particular has stood the test of time below 50 GHz, its underestimation of small drops in light rain should give values of attenuation which are too low at higher millimeter wavelengths according to Watson.[33] This has been the case with the results of Keizer et al.[28] Waldvogel reported that the proportion of small drops can be much higher in a

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[33]M. Watson, 1976, "Survey of Measurements of Attenuation by Rain and other Hydrometeors," Proc IEEE, 123:863

[28]W. P. M. N. Keizer, J. Snieder, and C. D. de Haan, 1978, "Rain Attenuation Measurements at 94 GHz: Comparison of Theory and Experiment," EPP Symposium, Neubiberg bei München, Germany

thunderstorm than in a uniform widespread rain of similar rainfall.[15] As recently as 1978, Kharadly et al analyzed over 100 hr of rain activity and found several instances where the measured attenuation was outside the limits of Joss's distributions[19] which enclose all values of the Laws-Parsons distribution. In the light of Keizer and Kharadly's findings, it may be instructive to examine Ugai et al 1977 work more closely.[12] After noticing that their measured attenuation was two or three times the value predicted by the Laws-Parsons distribution, the authors measured drops down to the 0.05 mm range by improvements in the first two techniques for directly measuring raindrop sizes listed on page 9. A comparison of Ugai et al and the Marshall-Palmer/Laws-Parsons distributions can be made with figures 4 and 5. Both are in the same units of number of drops per volume and rainfall rate. Three points become evident:

1. There are more drops in the below 0.5 mm range than a simple extrapolation of large diameter data would predict as in the Marshall-Palmer and Laws-Parsons distributions.

2. The proportion of drops in each size class remains about the same regardless of the rainfall intensity. This is not the case in the theoretical distributions where lighter rainfalls have proportionately more small raindrops.

3. At drop sizes 0.5 mm or larger all distributions are in agreement, a point made by the authors in their paper.

More data are needed in the size range below 0.3 mm to substantiate or refute the findings of Waldvogel and Ugai et al. However, this substantiation or refutation can be done only by improving or developing disdrometers capable of counting in this range with response times of less than a second. Also, more disdrometers need to be employed at one time to delineate the microstructure of a rainfall event. Three disdrometers appear to be the maximum number placed out for a millimeter experiment at this date,[40] probably because disdrometers are electronic devices and expensive compared to tipping bucket rain gauges. One ingenious way to circumvent this problem is to find the path-averaged distribution of raindrops and rain rate with a single instrument. Such

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[15] A. Waldvogel, 1974, "The N_0 Jump of Raindrop Spectra," J Atmos Sci, 31:1067

[19] M. M. Kharadly, J. D. McNicol, and J. B. Peters, 1978, "Measurement of Attenuation Due to Rain at 74 GHz," EPP Symposium, Neubiberg bei München, Germany

[12] S. Ugai, K. Kato, M. Nishijima, T. Kan, and K. Tazaki, 1977, "Fine Structure of Rainfall," Ann des Télécom, 32:422

[40] J. Sander, 1975, "Rain Attenuation of Millimeter Waves at λ = 5.77, 3.3, and 2mm," IEEE Trans Antennas Propagat, AP-23:213

a device projecting a laser beam along the rain path has been developed by the National Oceanic and Atmospheric Administration at Boulder, Colorado.[42]

Backscatter from Rain, $Z = AR^b$

During World War II, several workers[3,29] used Mie computations for theoretical investigations of the potential of monostatic radar to locate and characterize meteorological phenomena. Thus radar meteorology was born, a field which has been given a comprehensive treatment in the standard reference by Battan for frequencies up to about 40 GHz.[43] As in attenuation, a relation between equipment parameters (in this case, radar) and rainfall rate is needed for measurement purposes. This relation is the familiar Z-R relation, usually stated in the form:

$$Z = AR^b, \tag{4}$$

where

Z = reflectivity factor in m^2/m^3 (cross section/unit volume)

R = rainfall rate in millimeters per hour

A and b are dependent on frequency, temperature, etc.

In an extensive survey on radar rain backscatter before 1969, Stout and Mueller reported differences of more than 500 percent for the same rainfall among investigators.[44] One source of error is the small area sampled by rain gauges or disdrometers compared to the area underlying a radar resolution cell. Radar and a single tipping bucket rain gauge can differ by a factor of two in estimating the amount of rain in a

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[42]Ting-i Wang, K. B. Earnshaw, and R. S. Lawrence, 1979, "Path-averaged Measurements of Rain Rate and Raindrop Size Distribution Using a Fast-response Optical Sensor," J Appl Meteorol (in print)

[3]K. L. S. Gunn and T. W. R. East, 1954, "The Microwave Properties of Precipitation Particles," Quart J Roy Meteorol Soc, 80:522

[29]J. W. Ryde, 1946, "The Attenuation of Centimeter Radio Waves and the Echo Intensities Resulting from Atmospheric Phenomena," JIEE, Vol 93, Part IIIA, No. 1, p. 101

[43]L. J. Battan, 1973, Radar Observation of the Atmosphere, Chicago: The University of Chicago Press

[44]G. E. Stout and E. A. Mueller, 1968, "Survey of Relationships Between Rainfall Rate and Radar Reflectivity in the Measurement of Precipitation," J Appl Meteorol, 7:465

cell.[45] Even with seven tipping buckets, Desautels and Gunn found that if a single averaged relation $Z = AR^{1.6}$ derived from five storms was used to find the amount of rainfall for one storm, errors ranging from -35 to +54 percent could result.[46] On the other hand, Joss and Waldvogel in a paper presented at the same radar meteorology conference claimed to double the accuracy of radar rain measurements by the use of the A-R relations corresponding to their drizzle, widespread, and thunderstorm conditions.[47] Stout and Mueller also classified Z-R relations by general meteorological conditions. After examining 44 pairs of A and b values by 13 investigators in their paper, they concluded that differences appear to be related primarily to geographic area, and secondarily to rain type (continuous, showers, thunderstorms) and synoptic class (fronts, occlusions, waves, etc.).[44]

During the past decade, agreement between theory and measurement at centimeter radar frequencies has been generally good[48,49] probably with improvement in meteorological instrumentation. Another reason for good results is that centimeter radar operates in the Rayleigh region where raindrop diameter is small compared to wavelength and drop shape is not important. The reflectivity factor Z becomes independent of wavelength and can function as a method of comparing

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[45] M. C. Hodson, 1970, "Rainfall Rate Variation Within a Radar Resolution Cell," Am Meteorol Soc, 14th Radar Meteorol Conference, Tucson, AZ, p. 241

[46] G. Desautels and K. L. S. Gunn, 1970, "Comparison of Radar with Network Gauges," 14th Radar Meteorol Conference, Tucson, AZ, p. 239

[47] J. Joss and A. Waldvogel, 1970, "A Method to Improve the Accuracy of Radar Measured Amounts of Precipitation," J Atmos Sci, 26:566

[44] G. E. Stout and E. A. Mueller, 1968, "Survey of Relationships Between Rainfall Rate and Radar Reflectivity in the Measurement of Precipitation," J Appl Meteorol, 7:465

[48] N. C. Currie, F. B. Dyer, and R. D. Hayes, 1975, "Some Properties of Radar Returns from Rain at 9.375, 35, 70, and 95 GHz," IEEE International Radar Conference, p. 215

[49] R. K. Crane and H. K. Burke, 1978, "The Evaluation of Models for Atmospheric Attenuation and Backscatter Characteristic Estimation at 95 GHz," ERT Document No. P-3606, Environmental Research and Technology, Inc., 696 Virginia Rd, Concord, MA 01742

backscatter at different wavelengths.[8] Generally at these low frequencies, Z, as well as attenuation, increases as the rain rate increases.[48]

At millimeter frequencies, the larger drops are comparable in size to the wavelength and frequency-dependent Mie scattering dominates, although very small drops may still be Rayleigh-scattered as in the case of fog droplets. For Mie-scattered waves, the actual drop-size distribution is the most important factor to consider.[48] Theoretical rain backscatter computations, often based on the Laws-Parsons distribution, have been extended into the millimeter region by several workers.[8,35,50,51] According to Richard and Kammerer,[52] the Soviets have published extensively on theory--at times based on their own distributions--but have done no measurements to verify their findings.

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[8]R. L. Mitchell, 1966, "Radar Meteorology at Millimeter Wavelengths," Aerospace Corporation, Report TR-669(6230-46)-9, AD 488085

[48]N. C. Currie, F. B. Dyer, and R. D. Hayes, 1975, "Some Properties of Radar Returns from Rain at 9.375, 35, 70, and 95 GHz," IEEE International Radar Conference, p. 215

[35]R. K. Crane, 1966, "Microwave Scattering Parameters for New England Rain," Lincoln Lab MIT Technical Report 426, AD 647798

[50]A. Downs, 1975, "A Model for Predicting the Rain Backscatter from A 70-GHz Radar," BRL Memorandum Report 2467, AD A009699

[51]D. E. Setzer, 1970, "Computed Transmission Through Rain at Microwave and Visible Frequencies," Bell System Tech J, 49:1873

[52]V. W. Richard and J. E. Kammerer, 1975, "Rain Backscatter Measurements and Theory at Millimeter Wavelengths," US Army Ballistic Research Laboratory, Report No. 1838, Aberdeen Proving Ground, MD 21005, AD B00817L

Also in the West, millimeter measurements of backscatter are almost nonexistent except for the multiwave experiment to be discussed next.[49]

The multiwave backscatter experiment at 10, 35, 70 and 95 GHz at rain intensities from 1 to 100 mm/hr by Richard and Kammerer[52] is the most thorough work to date on rain backscatter at millimeter wavelengths. Especially valuable is the ability to relate commonplace X-band (10 GHz) backscatter data (reportedly in good agreement with theory) to scatter at higher frequencies for the same rain condition. For meteorological data, raindrop-size distributions for short periods were taken along with longer duration tipping bucket readings. The authors claimed good agreement at all frequencies. They found only a 5 dB maximum difference between their measured backscatter and theoretical values based on several distributions. Particularly satisfying was the decrease in backscatter above 70 GHz predicted by theory. Although the authors and Crane who reviewed this experiment in 1978[49] believe that theory based on known average drop-size distributions has been shown to be valid, they caution that not enough is known about drop-size distributions to calculate reliable estimates of backscatter for any short-time event. It would be instructive to eliminate rainfall rate and errors associated with its computation by plotting simultaneous values for backscatter for pairs of frequencies as were done by British investigators for one-way attenuation.[38,41]

In summary of the foregoing, backscatter, like attenuation, shows agreement between theory and measurement at millimeter wavelengths although measurements are very meager at this time. There is also the same need to characterize the raindrop spectra in space and time.

FOGS AND CLOUDS

The small particle sizes of fogs and clouds permit the use of Rayleigh approximations at millimeter frequencies;[3] therefore, attenuation is

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[49] R. K. Crane and H. K. Burke, 1978, "The Evaluation of Models for Atmospheric Attenuation and Backscatter Characteristic Estimation at 95 GHz," ERT Document No. P-3606, Environmental Research and Technology, Inc., 696 Virginia Rd, Concord, MA 01742

[52] V. W. Richard and J. E. Kammerer, 1975, "Rain Backscatter Measurements and Theory at Millimeter Wavelengths," US Army Ballistic Research Laboratory, Report No. 1838, Aberdeen Proving Ground, MD 21005, AD B00817L

[38] A. M. Zavody and B. N. Harden, 1976, "Attenuation/Rain-rate Relationships at 36 and 110 GHz," Electronics Letters, 12:422

[41] K. I. Ho, N. D. Mavrokoukoulakis, and R. S. Cole, 1978, "Rain-induced Attenuation at 36 GHz and 110 GHz," IEEE Trans Antennas Propagat, AP-26:873

[3] K. L. S. Gunn and T. W. R. East, 1954, "The Microwave Properties of Precipitation Particles," Quart J Roy Meteorol Soc, 80:522

independent of particle size distribution[7] and consists almost entirely of molecular absorption.[53] Attenuation is very dependent on liquid water content and temperature.[8] Theoretical calculations by Koester and Kosowsky[54,55] at millimeter wavelengths reveal that a low-temperature fog may more than double the attenuation caused by a tropical fog for the same liquid water content.

Despite the strong temperature dependency, fog droplets attenuate millimeter waves about one order of magnitude less than raindrops. This difference is seen by the following range of values taken from Rainwater[5] for 35 and 95 GHz:

Fog	0.034 - 0.47	dB/km
Rain	0.24 - 4	dB/km

Rain appears to be more significant in affecting millimeter waves than fog or clouds. However, confirmation is needed in cold advective fogs which theory predicts as the worst-case condition.

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[7]W. L. Gamble and T. D. Hodgens, 1977, "Propagation of Millimeter and Submillimeter Waves," US Army MIRADCOM Technical Report TE-77-14, AD B023622

[53]R. D. Etcheverry, G. R. Heidbreder, and W. A. Johnson, 1967, "Measurements of Spatial Coherence in 3.2mm Horizontal Transmission," IEEE Trans Antennas Propagat, AP-15:136

[8]R. L. Mitchell, 1966, "Radar Meteorology at Millimeter Wavelengths," Aerospace Corporation, Report TR-669(6230-45)-9, AD 488085

[54]K. L. Koester and L. H. Kosowsky, 1970, "Attenuation of Millimeter Waves in Fog," Amer Meteorol Soc, 14th Radar Meteorol Conference, Tucson, AZ, p. 231

[55]K. L. Koester and L. H. Kosowsky, 1971, "Millimeter Wave Propagation in Fog," IEEE Antennas and Propagation Symposium, Los Angeles, CA, p. 329

[5]J. H. Rainwater, 1977, "Weather Affects MM Wave Missile Guidance Systems," Microwaves, September, p. 62

TURBULENCE

Small-scale fluctuations at centimeter and millimeter frequencies, particularly of atmospheric water vapor, are known to cause local changes in the refractive index. It follows then that limitations may be imposed on instruments relying on the spatial and temporal coherence of wavefronts such as radio interferometers and pencil beam tracking radars.[53*] Field experiments in Hawaii,[56,57] the British Isles,[58-61] and the Soviet Union[62,63] strongly suggest that Tatarski's theory of optical wave propagation through a turbulent medium[64] as further developed by Clifford and Strohbehn[65] and Ishimaru[66] may be useful in gauging the magnitude of scintillations experienced by millimeter waves in the lower atmosphere.

In England, Mavrokoukoulakis et al found that the frequency spectra of amplitude fluctuations at 36 GHz and 110 GHz followed Tatarski's -8/3 power law, and the ratio of the fluctuations followed Ishimaru's formulas for comparing two radio frequencies.[61] The authors also found good agreement with the experimental work in Hawaii which compared 9.6 to 34.5 GHz.[56]

To apply Tatarski's theory, an estimate of the physical length of the outer scale of turbulence is needed. One indirect way is to derive it from the variances computed for the phase or amplitude fluctuations at two frequencies.[60] The most direct way pertinent to millimeter and centimeter wavelengths is to obtain the spectral density of water vapor fluctuations C_ρ^2 during the experiment. However C_ρ^2 is a difficult measurement to obtain, and it is customarily found indirectly through values of the outer scale of the refractive index or the temperature fluctuations, C_n^2 or C_T^2, respectively.[59,60] The scintillation and temperature experiment of Ho et al[59] is a straightforward example of how an estimate of C_T^2 is used to independently verify that the signal scintillations are within the limitations imposed by the conditions of Tatarski's theory. The authors found an outer scale of about 25 m.

In summary of turbulence at millimeter wavelengths, millimeter-wave scintillations may be explainable by an extension of Tatarski's theory from optical wavelengths. However, there is need to measure the outer scale of turbulence during millimeter-wave experiments because this scale is needed to apply Tatarski's theorems, and data are virtually nonexistent at this date.

CONCLUSIONS

No lengthy conclusion is included here since this report is a survey intended to present the atmosphere's effect on millimeter waves. Instead,

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*See reference section for references cited on this page.

the reader is referred to the summaries at the end of the major breakdowns of the report. Most of this review is on rain and raindrop-size distributions. This is appropriate because rain, the most common non-gaseous constituent of the lower atmosphere, also has the greatest effect on millimeter waves, and raindrop-size distributions are needed to compute the actual and theoretical effect of rain on radio wave propagation. The common thread running through this review is the still pressing need to acquire short-time data on raindrop-size distributions, particularly in the smallest size classes. Similarly, data on atmospheric fluctuations are needed to study the behavior of millimeter waves in turbulence.

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1400 Wilson Blvd
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1400 Wilson Blvd
Arlington, VA 22209

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